AFRL-RZ-WP-TP-2009-2153

HARDWARE-IN-THE-LOOP POWER EXTRACTION USING DIFFERENT REAL-TIME PLATFORMS (PREPRINT)

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JULY 2008

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AIR FORCE RESEARCH LABORATORY
PROPULSION DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7251
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
July 2008	Journal Article Preprint	01 July 2008 – 01 July 2008

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
HARDWARE-IN-THE-LOOP POWER EXTRACTION USING DIFFERENT REAL-TIME PLATFORMS (PREPRINT)	FA8650-04-D-2409-0004
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 62203F

6. AUTHOR(S)	5d. PROJECT NUMBER
John McNichols, Caleb Barnes, Mitch Wolff, and Thomas Baudendistel (PC Krause and Associates, Inc.)	3145
Michael Corbett and Peter Lamm (AFRL/RZPE)	5e. TASK NUMBER 32
	5f. WORK UNIT NUMBER 314532ZF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
PC Krause and Associates, Inc. 3000 Kent Avenue, Suite C1-100 West Lafayette, IN 47906-1075 — Electrical Technology and Plasma Physics Branch (AFRL/RZPE) Power Division Air Force Research Laboratory Propulsion Directorate Wright-Patterson AFB, OH 45433-7251 Air Force Materiel Command United States Air Force	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSORING/MONITORING AGENCY ACRONYM(S)
Air Force Research Laboratory Propulsion Directorate Wright-Patterson Air Force Base, OH 45433-7251 Air Force Materiel Command United States Air Force	AFRL/RZPE
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S) AFRL-RZ-WP-TP-2009-2153

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
This article was presented at the 6th International Energy Conversion Engineering Conference (IECEC). (AIAA-2008-5728), 28-30 July, 2008, Cleveland, OH. PAO Case Number and clearance date: WPAFB-08-3896, 01 July, 2008.
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14. ABSTRACT
Aircraft power demands continue to increase with the increase in electrical subsystems. These subsystems directly affect the behavior of the power and propulsion systems and can no longer be neglected or assumed linear in system analyses. The complex models designed to integrate new capabilities have a high computational cost. Hardware-in-the-loop (HIL) is being used to investigate aircraft power systems by suing a combination of hardware and simulations. This paper considers two different real-time simulators in the same HIL configuration. A representative electrical power system is removed from a turbine engine simulation and is replaced with the appropriate hardware attached to a 350 horsepower drive stand. Variables are passed between the hardware and the simulation in real-time to update model parameters and to synchronize the hardware with the model. Real-time simulation platforms from dSPACE, National Instruments (NI), are utilized for this investigation. Similar results are obtained when using HIL and a simulated load. Initially, noticeable differences are seen when comparing the results from each real-time operating system.

15. SUBJECT TERMS
hardware-in-the-loop, transient, turbine engine, simulation, real-time

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	SAR	14	Michael Corbett
					19b. TELEPHONE NUMBER *(Include Area Code)* N/A

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Hardware-in-the-Loop Power Extraction Using Different Real-Time Platforms

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Aircraft power demands continue to increase with the increase in electrical subsystems. These subsystems directly affect the behavior of the power and propulsion systems and can no longer be neglected or assumed linear in system analyses. The complex models designed to integrate new capabilities have a high computational cost. Hardware-in-the-loop (HIL) is being used to investigate aircraft power systems by using a combination of hardware and simulations. This paper considers two different real-time simulators in the same HIL configuration. A representative electrical power system is removed from a turbine engine simulation and is replaced with the appropriate hardware attached to a 350 horsepower drive stand. Variables are passed between the hardware and the simulation in real-time to update model parameters and to synchronize the hardware with the model. Real-time simulation platforms from dSPACE and National Instruments (NI) are utilized for this investigation. Similar results are obtained when using HIL and a simulated load. Initially, noticeable differences are seen when comparing the results from each real-time operating system. However, discrepancies in test results obtained from the NI system can be resolved. This paper briefly details the underlying problem and its solution before discussing test results which show that both dSPACE and NI can be configured to match the baseline Simulink data.

I.   Introduction

As a result of the new high-power capabilities being considered for aircraft, the potential for non-linear interactions between propulsion, power and thermal systems has arisen. Historically, such interactions were minimal and were neglected or assumed linear for integrated system analyses. Advanced modeling and simulation techniques are required to study these non-linear interactions and their system-level consequences. These increased power and thermal loads introduce large-scale dynamics that affect the entire aircraft. The high-power, low-efficiency loads introduce voltage transients that jeopardize electrical power quality and introduce large heat loads that encroach upon fuel temperature or component limits. Also, snap turbine engine power take-offs increase risks of engine stall, high mechanical stress, shaft breaks, and reduced thrust.

For advanced capabilities wherein the subsystem interactions are tightly coupled and no longer merely perturbational, the design and analysis must be performed at a high level to obtain a system-level power optimized aircraft. This type of integrated design and analysis will not only optimize performance, cost, weight, and volume but is essential if such advanced capabilities are to become feasible. Therefore, a computationally-efficient multi-physics system simulation must be utilized to address issues such as electric actuator power regeneration, fuel

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circulation for improved thermal management, and interactions between shaft power extraction and aircraft capabilities (speed, altitude, and maneuverability). In addition to dynamic interaction and system feasibility studies, this system simulation can also be utilized for prognosis and health management (PHM).

In this paper, the power and propulsion systems were exercised using electrical shaft power extractions from both the high pressure (HP) and low pressure (LP) spools. Although the size of the power and thermal loads may be smaller than would be required, these issues are conceptually similar since electrical shaft loading is a large percentage of the available turbine engine shaft power at high altitudes. Advanced integrated architectures were evaluated from a system-level perspective and compared with state of the art modeling and simulation methods in terms of power quality, stall margin, and shaft speed.

II. Background

Next generation aircraft requirements demand improved dynamic performance, power availability, emissions, reliability, and operability compared to present designs. To meet these requirements, preliminary design tools are needed that accurately model the transient phenomena of the power system. Recently, significant progress has been made in transient engine modeling utilizing MATLAB/Simulink[TM 1,2]. These dynamic models surpass the capabilities of traditional "cycle deck" performance models by considering time domain interactions of various components within the turbine engine. Using additional time-domain models allows a transient engine model to interface with other aircraft subsystems such as a power take-off generator and/or a full authority digital engine controller (FADEC).

Incorporating various transient subsystem level models into a complex modeling tool can be a challenging process when each subsystem model is in a different language. This issue can be resolved by utilizing DHS (Distributed Heterogeneous Simulation).[3] DHS is a software tool, which synchronizes any number of dynamic subsystem simulations using a wide variety of programs/languages. With this tool, there is no need or advantage to translate all models into a common language or to require that all models be developed in the same language.

III. Transient Turbine Engine Modeling

A generic turbine engine model in MATLAB/Simulink, which has not been validated with detailed experimental data, was utilized for this investigation. This model was based upon the work done by Gastineau, and a lumped component approach was used for ease of modification and replacement of engine components[4]. Each component was created with its own set of inputs and outputs, and was based on fundamental laws of physics such as the conservation of mass, momentum, and energy. In addition, gas tables were used to calculate properties such as enthalpy and specific heat for pure air or the fuel-air mixture as a function of temperature, pressure, and fuel-air ratio.

A multi-stage turbine or compressor was simulated as a single component. This approach was adopted because turbine and compressor maps are generally created in a lumped fashion and not stage-by-stage. Similarly, the combustor simulated combustion of a lumped amount of fuel and air in a control volume. It did not simulate the flame distribution or flame dynamics of the combustion process. This lumped, zero-dimensional approach is sufficient to capture the dynamics of interest for system integration studies.

The engine modeled in this paper was a two spool turbofan engine with the specifications shown in Table 1. A key feature of the Air Force Research Laboratory (AFRL) generic engine model is its ability to simulate transient conditions. Transient simulation, in addition to steady state analysis, is vital in the design, testing, and analysis of turbine engines. Dynamic system simulations capture overshoot characteristics of a turbine engine which could actually cause the engine to fail even though a steady state analysis might suggest stability.

The AFRL generic turbine engine model has been designed to be flexible. The component maps and engine layout can easily be changed to model various engine types. The controller that was used can also be modified or replaced as appropriate. In its current configuration, the generic turbine engine model's FADEC runs primarily on a fan speed limiter based on throttle setting. Different operating points can be specified by the user to examine the performance of the turbine engine by specifying parameters such as: deviation in ambient temperature from standard day

Specification	Value
Number of spools	2
Bypass ratio	4.9
LP spool design speed	8700 rpm
HP spool design speed	14,700 rpm
Altitude design	65,000 ft
Max altitude	70,000 ft
Mach number design	0.65
Max Mach number	0.65
Afterburner	None
Max steady state T4	3000 R

Table 1: Engine Design Specifications[5]

temperature, HP and LP shaft loading, throttle lever angle (TLA), altitude, and Mach number. Although the model allows the user to record any variable, this paper focuses on the LP and HP spool speed, power load on the LP and HP spools, and HPC (high pressure compressor) surge margin.

This model's level of complexity causes it to run about two times slower than real-time when using the *ode23t (Mod. Stiff/Trapezoidal)* variable step solver on a 2.0 GHz PC with 512 MB RAM and even slower yet when using the *ode4 (Runge-Kutta)* fixed-step solver and a 1 ms time step. To run the simulation in real-time, two platforms were tested: dSPACE and National Instruments' (NI) LabVIEW Real-Time. For both dSPACE and NI, the engine and FADEC were run together in a single simulation running on a single processor. The required convergence window for each model was 1 ms (the chosen simulation time step). The convergence time of the model on each system was well within the required window, suggesting that either real-time system would support more complicated models than the one used in these tests.

It is important to note that in order to produce accurate results using National Instruments' LabVIEW Real-Time, a workaround must be used to bypass an acknowledged software bug. Without the workaround, the NI real-time system produced inaccuracies in the results, most notably during transients, when compared to results obtained from the generic engine model running the same test in native Simulink (which is considered the "correct" data). The workaround consists of changing the "Tasking mode for periodic sample times" setting in the Simulink model's configuration parameters prior to building the model as a Dynamic Link Library (DLL) with Real Time Workshop. By default, this is set to "Auto" which allows the multi-rate model (engine and FADEC have different sample times) to attempt to use multi-tasking. This is apparently not handled properly by the NI real-time scheduler and should be changed to "Single-Tasking" to ensure accuracy when running on the NI platform. Results are presented with both settings to properly document this phenomenon.

The Simulink environment of the AFRL generic engine model facilitated a relatively smooth transition to both real-time environments using Real-Time Workshop along with software from each vendor. For the HIL configuration, variables within the simulation were mapped to hardware controls and feedback sensors using digital-to-analog converters (DAC) and analog-to-digital converters (ADC), respectively. In this study, LP spool speed was the primary parameter passed from the model to the 350 horsepower motor/generator drive stand. This model variable was converted to an analog voltage (0-10 V) which corresponded (linearly) to a speed control for the drive stand.

The drive stand was thus controlled by the real-time simulation to emulate the LP spool of a turbine engine, and was connected to an electrical power system implemented in hardware. This electrical power system included a generator, its generator control unit (GCU), and a resistor load bank. By switching on resistors in the load bank, an electromagnetic resistance (torque) was applied to the shaft by the generator. This was measured with a torque transducer and was fed back into the simulation. This LP shaft torque induced by the generator was used in the summation of shaft torques block within the model where it was subtracted (along with fan hub and fan tip torques) from the LP turbine torque output. The result was used to calculate a new LP shaft speed which was then commanded to the drive stand. The drive stand itself was physically capable of speeds up to 10,000 rpm, but the speed during testing was limited by the generator to approximately 8700 rpm. Ramalingam *et. al* demonstrated that the drive stand speed (as measured by a speed transducer) was able to track the model's LP spool speed.[6]

To test each of the real-time simulators, several integrated engine/power tests were performed. Some tests used an altitude of 60,000 ft, a Mach number of 0.6, and a TLA of 91%; others used an altitude of 65,000 ft, a Mach number of 0.55, and a TLA of 95%. Unless specified otherwise, the NI system used the "Single-Tasking" fix.

IV. Testing and Analysis

The first series of tests was designed to show that the HIL system accurately matches the "Sim Only" data (where the LP load was applied as an idealized step function within the simulation) for both dSPACE and NI. A step load of 74.4 kW on the LP spool was used for this demonstration. Altitude, Mach number, and TLA were all held constant at 65,000 ft, 0.55, and 95%, respectively for these tests. In addition, a constant 10 kW load was applied to the HP spool in simulation. Figures 1 through 4 show the results of these tests. Figure 1 shows the LP spool speed as a function of time for both the NI Sim Only and HIL configurations, with the corresponding HPC surge margin shown in Figure 2. Figure 3 shows the LP spool speed versus time for both dSPACE configurations (HIL and simulation only), with the HP spool speed for the same test plotted in Figure 4.

An engine cycle deck analysis for this test would only show the three steady state values (before the LP load is applied, with the LP load on, and after the LP load is removed) in each of Figures 1 through 4. With the ability to consider transient responses, the system is able to capture the dangerously low surge margin and possible stall which occurs between steady states (Figure 2); the large transient in LP spool speed (Figures 1 and 3) could cause reduced

thrust or power quality concerns. In this test the FADEC is enforcing a turbine inlet temperature limit, which is why the LP spool speed does not recover to its target speed while the LP load is applied (Figures 1 and 3). Each figure demonstrates excellent agreement between testing using a simulated LP load and a HIL LP load. Excellent agreement is also shown between HIL and Sim Only data sets for several other tests not presented in this paper. For this reason, HIL presents the ideal platform to consider both engine dynamics and electrical power quality (which is captured by the actual hardware response) during step loading of the LP spool.

Another series of tests was designed to compare the results between real-time systems during transient testing. In the first of these tests, a step load of 54.9 kW was put on the LP spool. All other variables were held constant: an altitude of 65,000 ft, Mach number of 0.55, and 95% TLA were used with a constant 10 kW load on the HP spool. To avoid uncertainty due to the generator hardware, this set of tests was conducted using the NI Simulation Only and dSPACE Simulation Only modes. Figure 5 shows the LP spool speed versus time. Once again, as with Figures 1 and 3, the FADEC limits the fuel flow due to a turbine inlet temperature limit and the LP spool is unable to return to its target speed. dSPACE and NI show good agreement for this test, with no apparent deviation during either of the transients or steady state points. Figure 6 shows the HPC surge margin as a function of time corresponding to the same test as Figure 5. As was seen in Figure 5, dSPACE and NI are in agreement for this parameter, with no apparent discrepancies between the two systems.

The next test in the series features the same 54.9 kW LP step load as the previous test. However, the constant operating conditions changed to an altitude of 60,000 ft, a Mach number of 0.6, and a 91% TLA. In addition, there was a constant 15 kW load on the HP spool for this test. Figure 7 shows the LP spool speed versus time. Unlike in Figures 1, 3, and 5, the FADEC is not in a temperature limited control loop in this test. Therefore, the LP spool is able to fully recover to its target speed at the load-on steady state. Figure 7 shows NI and dSPACE in excellent agreement for this test using Simulation Only datasets. Figure 8 shows the corresponding HP spool speed for this test. Like Figure 7, Figure 8 shows good agreement between dSPACE and NI, suggesting that either real-time simulator is capable of accurately running the dynamic engine model.

While Figures 1 through 8 suggest that both real-time systems produce accurate results compared to the same model running in native Simulink, this was only the case after "fixing" the model for running on NI. To demonstrate the problem, a test is run with a 74.4kW LP step load and all other variables are held constant: an altitude of 60,000 ft, a Mach number of 0.6, and a 91% TLA with a constant 15 kW load on the HP spool. Figure 9 shows the LP spool speed versus time for that test. It uses the "Auto" tasking mode (which becomes "Multi-Tasking" mode) in its Simulink setup. As in Figures 1, 3, and 5, the FADEC enforces turbine temperature limits and the LP spool cannot recover to its target speed. dSPACE is in excellent agreement with the results obtained from Simulink and NI has the same steady state speeds. However, NI is noticeably off during the transients. Considering other variables further illustrates the inability of the NI real-time scheduler to properly handle "Multi-Tasking" Simulink models.

Figure 10 shows the HPC surge margin versus time for the same test shown in Figure 9. It showcases the accuracy of the "Multi-Tasking" model on dSPACE, the error of the "Multi-Tasking" model when running on NI, and the accuracy of results obtained from the NI system when using the "Single-Tasking" option. Figure 10a shows that all data sets are in agreement except for the NI data set using auto-tasking. Figure 10b shows the same HPC surge margin plot, but is focused on the load-on transient which displays the discrepancy prominently. Figure 10c shows the same data again, but is zoomed in even further, specifically focused on the minimum surge margin and ringing phenomenon seen in three of the four data sets. While all steady state values, the load-off transient, and the minimum surge margin value are very close for all four data sets, there is a drastic difference in the shape of the load-on transient between NI with "Auto" tasking mode (which converts to "Multi-Tasking" when built) and Simulink. The Simulink model shows oscillations in the HPC surge margin near its minimum during the load-on transient (Figure 10c). While dSPACE accurately replicates this trend, the NI system using "Multi-Tasking" shows no oscillations of any kind and instead shows a relatively smooth curve through this section. However, when using the "Single-Tasking" option, results obtained from the NI system are fixed. NI then accurately matches the oscillations seen in the Simulink results (Figure 10c). More importantly, NI agrees with Simulink for the entire test, eliminating the hiccups or checkmarks seen in the results obtained from the NI system using "Auto" tasking mode (Figure 10b).

V. Conclusion

Transient propulsion and power system modeling has been investigated using a Simulation Only configuration and a HIL configuration with real-time simulation platforms from both dSPACE and National Instruments. Various experiments were performed using the LP generator as the hardware component in the loop. Significant non-linear, transient behavior occurred when the power loads were applied and removed. These events cannot be predicted

using traditional "cycle deck analysis" models. These transients could result in problems such as compressor stall, making it vital that transient events are modeled and that those models be exercised in integrated system analysis.

Excellent agreement was shown between the HIL and Simulation Only model results. These results are consistent with the results seen previously and further validate the capability of using HIL in propulsion and power experiments[7]. However, significant differences were initially seen between the results produced by the real-time systems, specifically during transients. While results obtained from the dSPACE real-time system are in good agreement with results obtained from the same model running in native Simulink, results obtained from the National Instruments system were not in agreement. Until a workaround provided by National Instruments' tech support was implemented with this fix, both dSPACE and National Instruments are in agreement with the results obtained from running the same model in native Simulink. These results show that both dSPACE and National Instruments' real-time operating systems can be configured to accurately run transient Simulink models for Simulation Only or for Hardware-in-the-Loop studies.
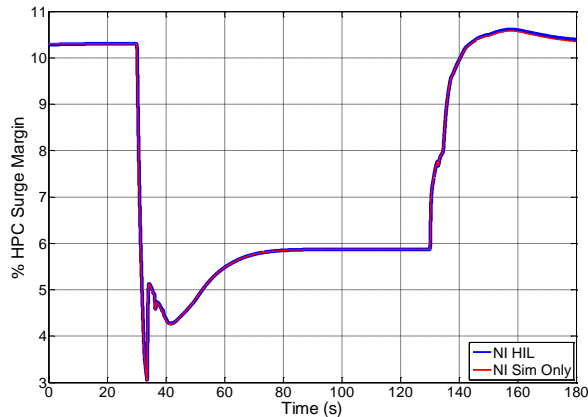
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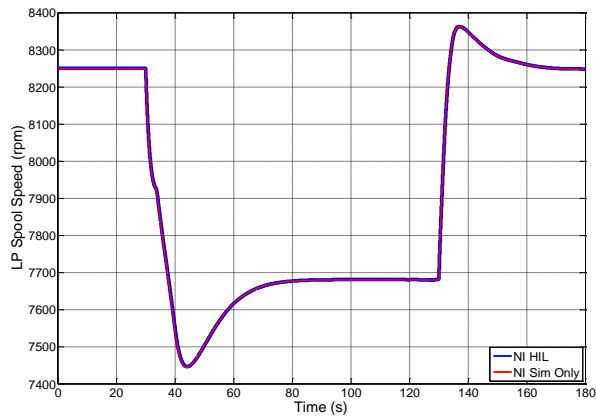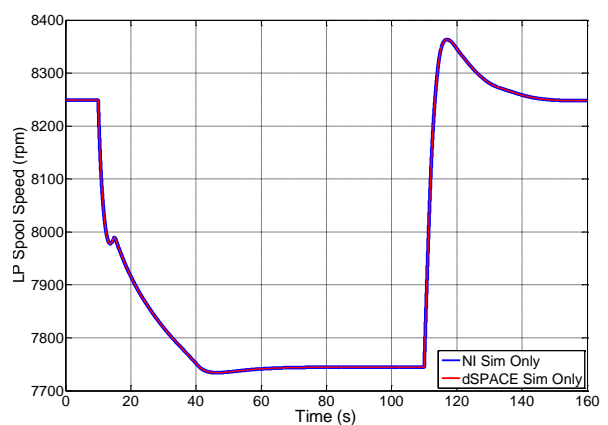
Figure 1: LP Spool Speed vs. Time – Comparison of HIL and Sim Only data from NI LabVIEW for a constant 10 kW HP load with a 74.4 kW step LP load.
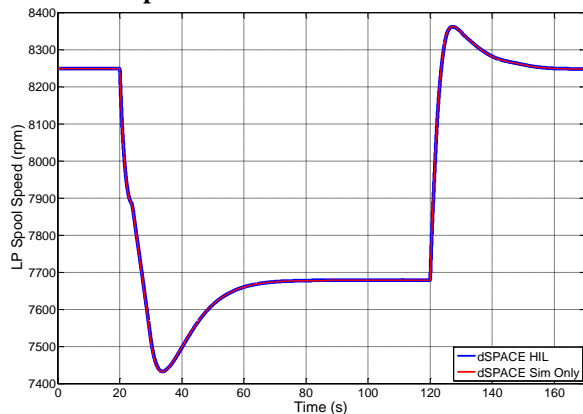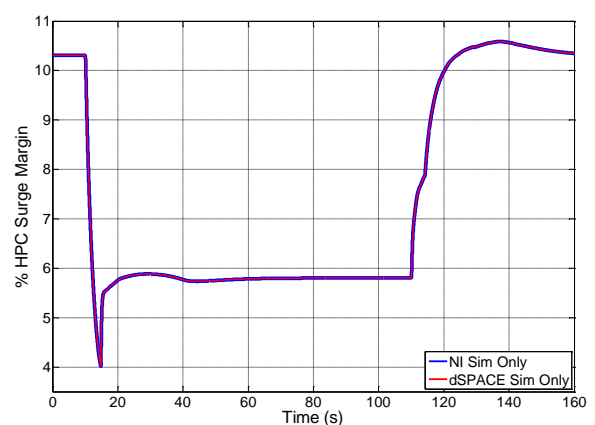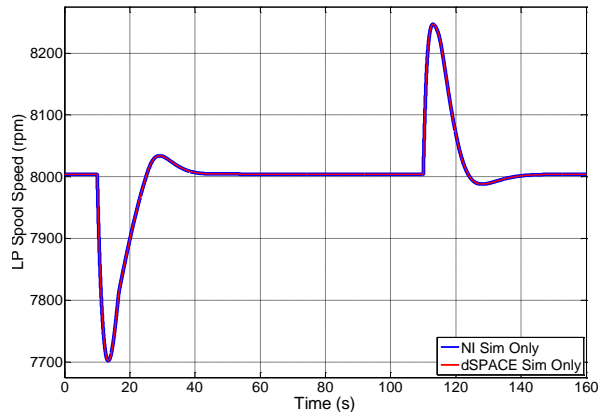

Figure 2: HPC Surge Margin vs. Time – Comparison of HIL and Sim Only data from NI LabVIEW for a constant 10 kW HP load with a 74.4 kW step LP load.

Figure 3: LP Spool Speed vs. Time – Comparison of HIL and Sim Only data from dSPACE for a constant 10 kW HP load with a 74.4 kW step LP load.
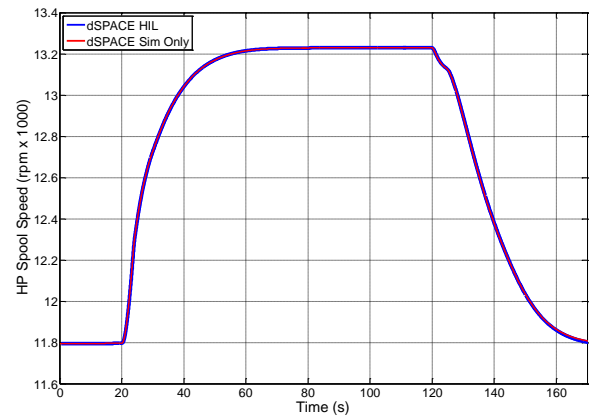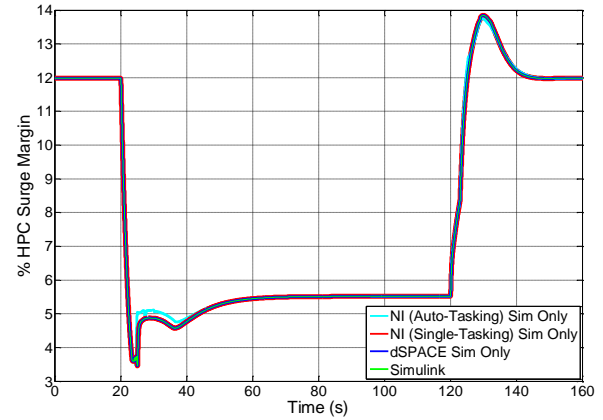

Figure 4: HP Spool Speed vs. Time – Comparison of HIL and Sim Only data from dSPACE for a constant 10 kW HP load with a 74.4 kW step LP load.

Figure 5: LP Spool Speed vs. Time – Comparison of NI and dSPACE for a constant 10 kW HP load with a 59.4 kW step LP load.

Figure 6: HPC Surge Margin vs. Time – Comparison of NI and dSPACE for a constant 10 kW HP load with a 59.4 kW step LP load.
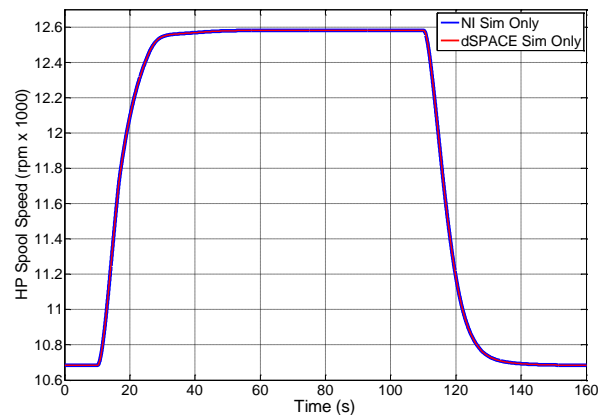
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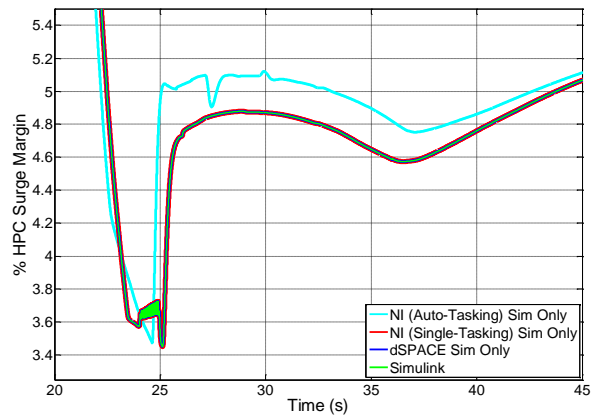
Figure 7: LP Spool Speed vs. Time – Comparison of NI and dSPACE for a constant 15 kW HP load with a 59.4 kW step LP load.
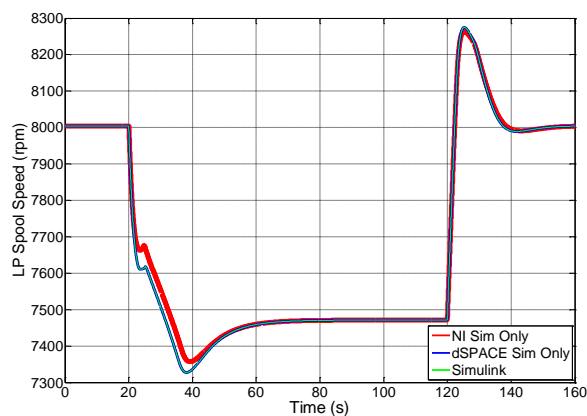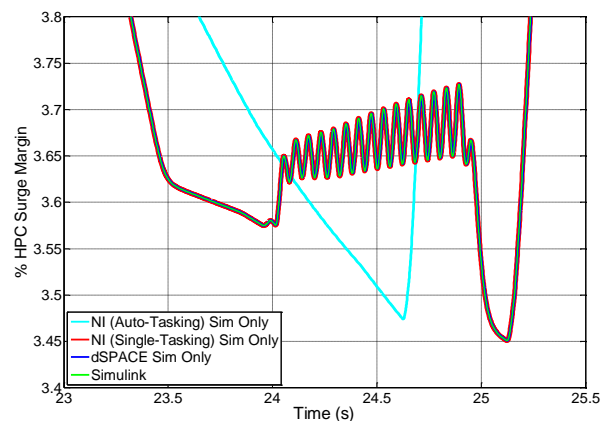

(a)

Figure 8: HP Spool Speed vs. Time – Comparison of NI and dSPACE for a constant 15 kW HP load with a 59.4 kW step LP load.

(b)

Figure 9: LP Spool Speed vs. Time – Comparison of NI and dSPACE to native Simulink for a constant 15 kW HP load with a 74.4 kW step LP load.

(c)

Figure 10: HPC Surge Margin vs. Time – Comparison of NI and dSPACE to native Simulink for a constant 15 kW HP load with a 74.4 kW step LP load.

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